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The Influence of Operating Conditions on Density Stratification in a Batch Jig

Part 1: The Influence on the Equilibrium Stratification Profile

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Abstract

The study reported in this paper is the first in a series of two that investigated the influence of operating conditions on stratification in a batch jig. This paper focuses on an equilibrium study; the next on a kinetic study. Based on testwork and a detailed consideration of which operating conditions were relevant to the study, four factors were identified as being the primary operating variables influencing stratification in the test jig at equilibrium. These were the pulsion time, the pulsion hold-time; the amplitude of the jig cycle; and the depth of the particle bed in the jig. All other factors were found to be either dependent variables, or to exert no significant influence on stratification at equilibrium. Based on 32 equilibrium tests, it was found that the equilibrium stratification profile was essentially independent of operating conditions within a broad range of values. This finding has both theoretical and practical implications. The most significant of these is that the influence which operating variables have on jig performance derive from their influence on stratification kinetics and not from their influence on stratification at equilibrium.

1. Introduction

The operating conditions in a mineral jig can influence both stratification kinetics and the stratification profile achieved at equilibrium. In the past, however, studies on stratification in jigs have focused either on one or the other; equilibrium studies have been conducted to investigate the quality of stratification achievable, while kinetic studies have been undertaken to understand how stratification progresses with time. To our knowledge, no studies have been undertaken that intentionally attempt to disentangle kinetic from equilibrium effects; i.e. that distinguish between how operating conditions influence, on the one hand, the quality of stratification achievable and, on the other, the rate at which that quality can be achieved.

There are several reasons for pursuing such a disentanglement. Firstly, any increase in the understanding of stratification fundamentals may have significant practical implications. Secondly, much progress has been made in the capability of mathematical models to predict the stratification profiles in jig beds once they have reached an equilibrium state. In particular, the ability of the King model (King, 2001) to predict the nature of density stratification at equilibrium has been well validated (King 1987; Tavares and King 1995; Woollacott et al. 2015). It is to be expected that the inherent limitations of that model will increasingly be overcome as research and model development progresses. Accordingly, it makes sense to extend the usefulness of being able to simulate or predict the nature of stratification at

equilibrium by developing the ability to predict how stratification progresses towards an equilibrium condition.

A third reason for investigating how equilibrium and kinetic effects might be disentangled is that the operating conditions in a jig may influence the two profiles differently and may do so in ways that have significant practical implications. Accordingly, an experimental study was undertaken to investigate how operating conditions affect equilibrium stratification profiles and how they affect the rate at which stratification profiles approach equilibrium. This paper presents the results of the equilibrium study. The follow-up paper presents the findings of the kinetic study.

2. Background

Stratification of a particle bed immersed in a vertically pulsating mass of water is at the heart of the jiggling process. It is the primary process active in batch jigs. In continuous jigs, jiggling performance is influenced by stratification dynamics along with other factors—such as particle remixing and horizontal fluid and particle movement (King, 2001). Accordingly, this study was conducted in a batch jig so as to focus exclusively on factors affecting stratification.

Jigs are distinguished by whether they are ‘over-screen’ or ‘through-screen’ jigs; whether they are pulsed through a side chamber or an under-screen system; and by the nature of the pulsing system itself which may be mechanical or pneumatic in nature (Burt, 1984). Mechanical systems consist of either a cam or piston that moves a diaphragm or bellows up and down so that the water level in the jig chamber moves up and down in sympathy. Pneumatic systems employ what is in effect an ‘air piston’—an air chamber that is pressurized and depressurized so that the change in volume causes the water level in the jig chamber to move up and down in sympathy.

The batch jig used in this study relates to an over-screen jig, with an under-screen pulsing system consisting of a piston and bellows. The piston was driven pneumatically and its movement was controlled through a PLC as has been described elsewhere (Woollacott and Silwamba, 2016). The jig chamber was circular in cross-section; 200mm in diameter; and consisted of a set of rings clamped together so the chamber was water tight. At the end of a test, i.e. after 999 seconds, the clamps were released and the jig bed sliced into layers by inserting a thin slide plate between the rings. The contents of each layer were then dried, sorted manually by colour, and their composition determined so that the stratification profile in the jig bed could be established.

Figure 1 illustrates the way stratification profiles were described and analysed in the study. It envisages the bed being split into an upper product and a lower product, and indicates the recovery of each particle component to the upper layer as a function of the split height.

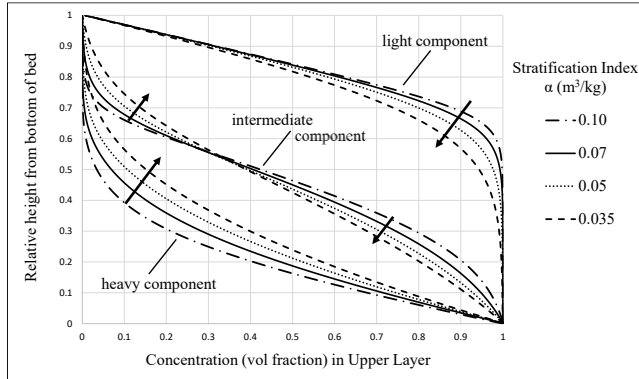


Figure 1: Effect of quality of stratification on stratification profiles
(The arrows in the diagram indicate deterioration in the sharpness of stratification.)

The figure also indicates the effect of the quality of stratification on the profiles at equilibrium. These profiles have been calculated using King's model (King, 2001) for density stratification with the quality of stratification (i.e. the sharpness of stratification achieved) being defined in terms of the King stratification index, α . Equation 1 summarises that model.

$$\frac{dC_j(h)}{dh} = -\alpha C_j(h)[\rho_j - \bar{\rho}(h)] \quad , \quad j = 1 \text{ to } N. \quad [1]$$

Here $C_j(h)$ is the volumetric concentration of particles having a density ρ_j in the very thin horizontal layer in the bed located at a relative height h to $h+dh$ from the bottom of the bed, i.e. $h=H/H_{bed}$ where H is the actual height of the bottom of the thin layer and H_{bed} is the height of the bed. N is the number of particle components in the bed and $\bar{\rho}(h)$ is the mean density of particles in the thin layer at h . In Figure 1, the recovery of component j to the upper layer, $\bar{R}_j(h)$, is calculated from Equation [2] for a given concentration of j in the bed as a whole, C_j^{feed} .

$$\bar{R}_j(h) = \int_h^1 C_j dh / C_j^{feed} \quad [2]$$

The stratification index α provides a useful, single parameter descriptor for equilibrium stratification profiles; the greater the value of α , the sharper the stratification. The arrows in Figure 1 illustrate what happens to the stratification profiles when the quality of stratification deteriorates, i.e. when α decreases.

An investigation into the effect of operating conditions on the equilibrium stratification profile first requires that the relevant operating conditions be clearly identified and specified. This is done in Part A of the paper. Part B then presents the findings of the equilibrium study.

PART A: Identification of Operating Variables that Affect Stratification

3. Preliminary Identification of Relevant Operating Variables

A literature search identified 15 variables that can potentially influence the nature and quality of stratification in a jig. These are introduced and discussed under 4 headings: properties of the

particle system; variables affecting the dimensions of the jig cycle; variables affecting the shape of the jig cycle; and other operating variables. In the course of the discussion, 7 of the variables identified were eliminated as not being relevant to this study. Testwork was then conducted to determine the relevance of the remaining 8 variables.

3.1 Properties of the Particle System Being Stratified

It is well known that the nature of stratification in a jig bed is influenced by the density, size and shape of the particles being stratified (Burt 1984). Denser, larger and less angular particles tend to stratify towards the bottom of the bed, while less dense, smaller and more angular particles tend to stratify towards the top of the bed. The ‘feed’ composition—i.e. the number of distinct particle components and their relative proportions in the material ‘fed’ to the jig—also affects stratification. For example, it is a boundary condition in the solution of Equation [1], and it influences $\bar{R}_j(\mathbf{h})$ directly in Equation [2].

Although these variables influence stratification, they are not operating variables as such. Operating variables will be considered to be those variables that jig operators can manipulate in their efforts to optimize stratification in a jig. Accordingly, the properties of the particles used in the testwork were not varied and a single sample of particles was in all tests. In order that stratification might be described in terms of the King stratification index, the study focused only on density stratification by using mono-sized spherical beads with a range of densities.

3.2 Operating Variables Affecting the Dimensions of the Jig Cycle

Stratification in a bed is strongly influenced by the nature of the jiggling cycle—its amplitude, frequency and shape (Rong and Lyman, 1992). The extent to which the bed is expanded or ‘dilated’ depends on how quickly and how far the water level rises during the ‘pulsion’ stage of the cycle. Bed dilation may be inadequate if the amplitude is too small or the vertical velocity of the pulsion stroke is too low (Burt 1984). As Table 1 indicates, amplitudes typically decrease with particle size; larger particles stratify best with a lower cycle frequency, typically 60 cycles per minute; and smaller particles stratify best with higher frequencies.

Table 1: Typical ranges of amplitude and frequency in industrial jigs
(Burt 1984, p 211)

Type of Jig	Particle size range (mm)	Amplitude (mm)	Frequency (cycles/min)
Baum	200-5	30-40	30-60
Batac	100-0.5	30-60	40-60
Diaphragm	25-0.25	20-30	125-150
Diaphragm	10-0.2	10-15	150-200
Pulsator	5-0.1	6-3	200-400

The jig cycle frequency (cycles/minute)—or its inverse, the cycle time (seconds/cycle)—is controlled through the settings on the jig pulsing system. Control of the amplitude of the jig cycle—specifically the amplitude of the water displacement in the jig chamber—is more complicated and depends on the type of jig. In mechanical pulsing systems, it is controlled by the length of the ‘stroke’ of the piston (or the extent of diaphragm movement) that causes the water to rise in the jig chamber. The operating variable is therefore some form of stroke setting, typically the ‘%Stroke’—i.e. the extent of movement of the piston driving the bellows as a percentage of its maximum range of movement.

The relationship between the stroke setting and the water displacement it generates is not straightforward. It depends on the geometry of the jig; on the response dynamics of the system driving the piston; and the velocity of that piston when activated. The velocity of the piston is typically controlled by the pressure of the compressed air driving the piston. The stroke-displacement relationship is usually not linear and, if the actual water displacement is to be used directly as the operating variable, the relationship needs to be calibrated. In this study, the three operating variables controlling the dimensions of the jig cycle were frequency, %Stroke, and the pressure of the compressed air to the piston drive system.

In pneumatic pulsion systems, the control of the amplitude of the jig cycle is intimately interlinked with the control of the shape of the jig cycle as discussed next.

3.3 Operating Variables Affecting the Shape of the Jig Cycle

The shape of the jig cycle—how the water displacement changes with time during the cycle—affects the dynamics of particle and fluid movement in the jig bed and hence the nature of the stratification that takes place.

In cam-driven pulsion systems the shape of the cam provides a very direct means of controlling shape of the jig cycle. In piston driven pulsion systems, the same kind of direct control is achieved by controlling the movement of the piston. In pneumatically driven jigs, however, the control of the shape and amplitude of the jig cycle is less direct because it is mediated through the peculiarities of the ‘air piston’ and how it is applied. Air is introduced into one or more air chambers for a period T1 (the pulsion time) to raise the water level in the jig; the pressure is maintained for a further period T2 (the pulsion hold-time); the chamber is then depressurized for a period T3 (the exhaust time); and then may be held in that state for a period T4 (the exhaust hold-time). This is illustrated in Figure 2. The way the water level responds to this pressurization and depressurization, however, is complicated by the compressibility of air and how it behaves in the dynamic system of the pulsion scheme. The complexity of this response is vividly evident in the work of Rong and Lyman (1991, 1992, 1993).

In this study, the complications associated with the use of an air piston were avoided by employing a mechanical piston-bellows pulsing system. However, the control of the piston movement mimicked the control scheme used in pneumatic jigs. The piston moved upwards for a period T1, was held there for a period T2, was then lowered for a period T3 and then held for a period T4 before the cycle repeats. In this way, the shape of the jig cycle could be controlled by adjusting these four time periods. Figure 2 indicates how the water displacement responded to a particular selection of these time periods. It also indicates how the bed displacement responded to the water displacement pattern.

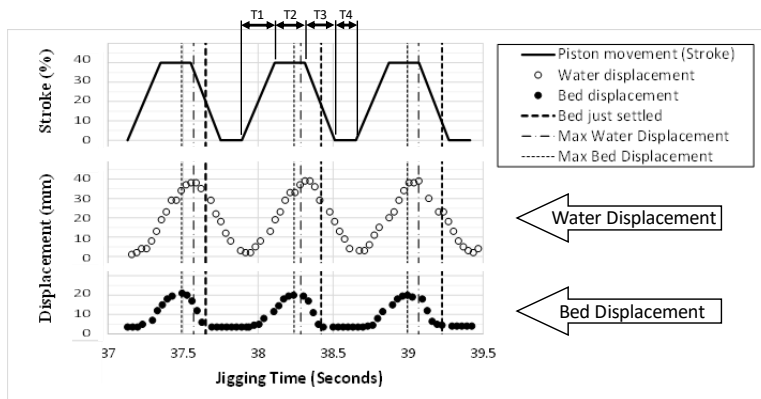


Figure 2. Relationship between pulsation scheme, water displacement, and bed displacement (The displacements in the jig chamber were measured from a video of the bed motion.)

In summary, the control of the jig cycle amplitude, frequency and shape was exercised in the study by adjusting 6 variables. The four time periods T1 to T4 determined the shape of the jig cycle. The %Stroke and the air supply pressure exerted primary control over the cycle amplitude. The frequency of the cycle is a dependent variable once T1 to T4 were set; it was determined by the inverse of the total cycle time—i.e. $1/(T1+T2+T3+T4)$.

Of these 6 variables only 5 were relevant to the study. This can be appreciated by reference to Figure 2. It can be seen that the suction hold-time, T4, is essentially dead time as far stratification processes are concerned; the bed is consolidated and static during this period and interstitial trickling is absent in a system of mono-sized particles. Therefore, it is not a variable that will have any effect on the quality of stratification and so can be fixed at some convenient value.

Several workers have investigated how other variables associated with the shape of the jig cycle affect stratification. For example, Rong and Lyman (1991, 1992, 1993a, 1993b) have investigated the influence of the velocity and acceleration of the water displacement. These variables, however, are dependent variables that depend on the shape and amplitude of the jig cycle and so were not considered further in this study.

3.4 Other Operating Variables

The fact that the pulsion and suction stages in a jig cycle involve the flow of water through a packed or partially fluidized particle bed means that the characteristics of that bed are likely to influence the way in which it responds to pulsion and suction. The most obvious characteristic is the depth of the bed (Burt, 1984). The amount of energy needed to lift and dilate a jig bed is determined by the density and depth of that bed. To dilate a deep bed, for example, requires more power than is needed for a relatively shallow bed.

A second characteristic is the water level in the jig. It determines the extent to which the particle bed is fully immersed during a jiggling cycle. If the water level drops below the top of the particle bed it enhances the tendency for smaller particles to trickle through interstices in the bed during the suction cycle (Burt 1984). Over-screen jiggling usually employs a fully

flooded bed throughout the jig cycle, so the immersion pattern of the bed was not considered to be a variable that was relevant to the study.

The hutch water flowrate is a third operating variable that can affect stratification in a jig (Rong and Lyman, 1992). Hutch water—the upward flow of water into the jig chamber through the screen supporting the particle bed—is likely to affect bed dilation and hence the stratification dynamics in a jig. The hutch flow contributes to the dilating effect of the pulsion stroke and diminishes the effect of the suction stroke. In a continuous jig, hutch water is always needed to compensate for the water that flows out of the jig chamber with the lights product stream. In a batch jig, water is not lost from the chamber in this way and so the addition of hutch water is optional.

Perhaps the most significant operating variable of all is jiggling time (Rong and Lyman, 1992). It takes time for a particle bed to stratify and to move from a homogeneous condition to a fully stratified one at equilibrium. An investigation into the influence of stratification kinetics is the subject of the second paper in this series.

4. Testwork to Identify the Relevance of the Operating Variables

The observations so far have identified 8 operating variables that can influence density stratification in a batch jig that employs a mechanical pulsing system. These are frequency (or cycle time); %Stroke; the pressure of the air supply; T1, T2, and T3; the depth of the bed, and the flowrate of hutch water. Testwork was carried out to investigate the relevance of these variables to the study.

Figures 3a and 3b show that the hutch water flowrate had little if any influence on the stratification profile of the particle system used in the study. Figure 3a shows virtually identical stratification profiles at three flowrates; there is perhaps a very slight increase in the sharpness of stratification at equilibrium when the hutch flowrate increased from 0 to 10 and 15 L/min. Figure 3b shows virtually identical profiles at 100s jiggling time for hutch flow rates of 0 and 15 L/min.

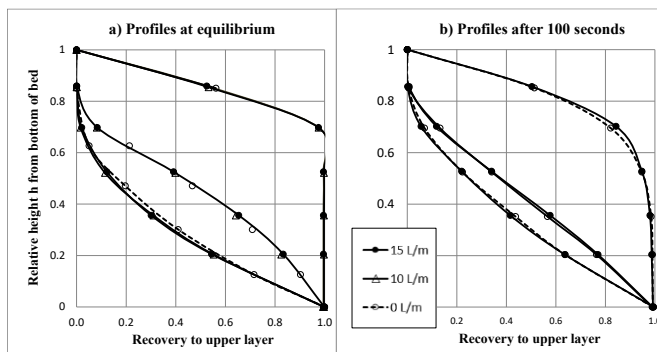


Figure 3: The effect of hutch water flowrate (litre/minute) on stratification profiles at equilibrium (Figure 3a) and after jiggling for 100s (Figure 3b)

To investigate the relevance of the 6 variables associated with the nature of the jig cycle (i.e. bed depth was excluded from this investigation), a 2^{6-1} partial factorial experimental design was undertaken based on the conditions outline in Table 2 and the associated testing schedule suggested by the software package Design Expert 7.0. The response variable was the magnitude

of the water displacement in the jig chamber as measured from video recordings of 35 tests. The water and bed displacement patterns shown in Figure 2 derive from one of these tests.

The regression model that emerged from an analysis of the data from these tests is presented in Table 2 along with the related statistics. Figure 4 compares the measured water displacements with the predictions from the regression model. The adjusted regression coefficient, R^2 , is 0.93.

Table 2: The ranges of operating variables tested in the partial factorial design (The bed depth for all tests was 80mm. The variable values selected were based on previous experience with the test jig. The beads used were spherical, 8mm in diameter and had a density of 2567 kg/m³.)

Range of test values	A:T1 (sec)	B:T2 (sec)	C:T3 (sec)	D:I/T5 frequency (cycles/min)	(T5*) cycle time (sec)	E: Stroke %	F:Pressure psi				
lower value (-1)	0.14	0.2	0.2	45	(1.33)	30	59				
center point (0)	0.18	0.25	0.25	60	(1.0)	35	67				
upper value (+1)	0.22	0.28	0.28	77	(0.78)	40	75				

The regression model equation is: Water displacement (mm) = \sum (coefficient x parameter value)
Parameters are dimensionless – having values -1, 0 or +1.

Parameter	intercept	A	B	D	E	F	AD	AE	BD	DE	ADE
Coefficient	34.88	2.49	4.44	-4.70	8.94	3.49	-1.69	0.93	-1.69	0.51	-1.63
p-value	<0.0001	0.0011	<0.0001	<0.0001	<0.0001	<0.0001	0.019	(0.18)	0.012	(0.46)	0.023
F value	32.2	13.6	43.5	48.4	175.5	26.8	6.3	1.9	6.2	0.6	5.8

* The cycle time T5 is included in the table for reference purposes only.

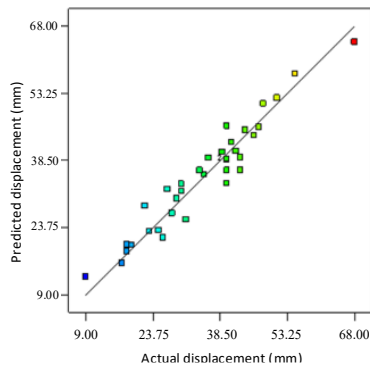


Figure 4: Measured water displacements compared with values predicted by the model

The analysis of the data indicates that T3 had no significant influence on water displacement in the study. The influence of the other 5 variables was found to be significant, as well as two two-factor interactions (i.e. between T1 and frequency; and between T2 and frequency) and a three-factor interaction (between T1, frequency, and %Stroke). The variables that were found to be most influential, as suggested by the associated F-values, were %Stroke followed by T2 and frequency. Although the influence of the air supply pressure was significant, it was less influential than those three variables. T1 was the least influential variable.

The lack of influence of T3 on stratification can be understood from the water and bed displacement data presented in Figure 1. The figure shows the bed to be fully consolidated well

before the end of the T3 period. Consequently, the time for the bed to achieve a fully consolidated state is not affected by the length of T3 provided it is just sufficiently long for bed consolidation to be completed; stratification dynamics essentially cease when the bed, consisting only of 8mm particles, is consolidated and static. The only function of the suction period, T3, therefore, is to allow the water and bed displacement to return to zero before the next jig cycle begins. Accordingly, T3 was eliminated as a relevant operating variable and its value was set at 0.25 seconds in all tests.

An implication of these observations is that the frequency of the jig cycle can be treated as a dependent variable; T3 and T4 have no influence on stratification and are set at convenient values; and T1 and T2 are the primary independent variables that influence the shape of the jig cycle. Accordingly, the cycle time T5 was set at a value well in excess of the likely maximum value of T1+T2+T3 that was likely to be used in subsequent tests. The value selected was 1.33 seconds which translates as a cycle frequency of 45 cycles/minute.

The movement of the piston in the pulsion unit is controlled by the %Stroke setting and the air-supply pressure. However, the dominant influence of %Stroke on water displacement in the jig suggested that the influence of air-supply pressure on stratification may be negligible. Preliminary stratification tests showed this to be true as discussed shortly. This finding was somewhat surprising given that the regression model in Table 2 suggested that air-pressure did influence water displacement significantly. This observation suggests that more attention should be given to bed displacement patterns than to water displacement patterns when evaluating the relevance of the operating variables on stratification in the jig.

In conclusion, the investigation to identify which operating variables were relevant to the study identified just four: %Stroke, T1, T2 and the depth of the jig bed.

PART B: The Influence of Operating Conditions on Stratification at Equilibrium

5. Experimental Design

To eliminate the influence of four particle properties (size, shape, number and proportion of components) on density stratification, the testwork was conducted using a fixed composition of (nominally) 8mm glass beads. Each test used exactly the same set of beads. Table 3 summarizes their properties. The density differences between the four types of beads varies in the range from 351 to 23 kg/m³. The small density differences between the green, red and blue beads are particularly relevant to practical contexts where incomplete liberation leads to many particles in a jig bed having small density differences leading to poor stratification behaviour.

Table 3: Properties of the glass beads used in the testwork

Bead type	Shape	Size (mm)	Density (kg/m ³)	Feed composition (volume%)	
				Investigation 1	Investigation 2
Matte (Boro)	Spherical	8.021	2226	22	26
Green	Spherical	8.19	2463	39	45
Red	Spherical	7.8	2554	19	29
Blue	Spherical with small 'equatorial' ridge	7.96	2577	20	0

Two investigations were conducted. The first, using a quaternary mix of the beads, was a 2⁴⁻¹ partial factorial experimental design to investigate how all four operating variables (T1, T2, %Stroke and bed depth) affected the equilibrium stratification profile. The response variable used in the design was the King Stratification Index (see Equation 1 and Figure 1). Unfortunately, as Figure 5 shows, the King model did not fit the stratification profiles

sufficiently well for the experimental design to be meaningful; the quality of the index as a reliable descriptor of those profiles was not sufficiently consistent for a meaningful analysis of the test results. The problem appeared to stem from the small differences in the size and shape of the bead components (see Table 3). The blue beads had a small ridge around their ‘equators’; and the combination of smaller denser beads (the red component) and larger but lighter beads (the green component) seemed also to be a problem. Accordingly, this investigation was not pursued further.

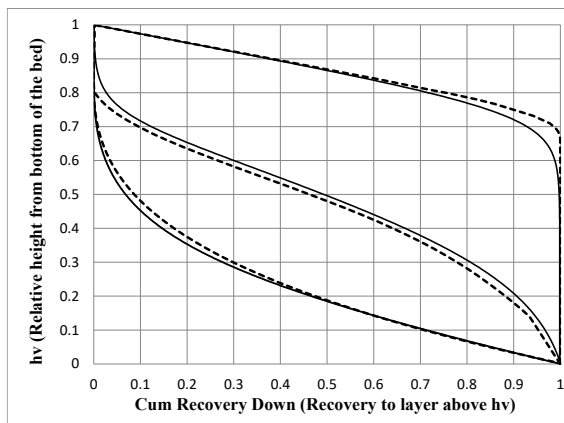


Figure 5: Measured and predicted equilibrium stratification profiles compared

The second investigation, using a ternary mix of the beads—i.e. without the blue beads—employed a less sophisticated experimental design necessitated by the inadequacy of the stratification index α as a descriptor of the equilibrium stratification profiles generated in the test. This inadequacy meant that an appropriate response variable was not available for a factorial design. Secondly, it meant that the stratification profiles could not be compared numerically in any simple way. Consequently, the analysis of the test results was based on comparing plots of the stratification profiles achieved under different operating conditions.

As will be seen, the analytical limitations of such graphical comparisons did not prove to be very detrimental to the study, particularly because the stratification profiles could be established with a high degree of precision. This is illustrated in Figure 6 which shows replicate tests at three different pressures of the air supply to the pulsation unit. What is evident from this figure is that, over the range of values tested, the air-supply pressure did not affect the equilibrium stratification profiles for the three bead components. In effect, the shapes of these profiles, as indicated by the dotted lines, have been established by 9 replicates in total. Almost all the data points fall on the curves exactly and so demonstrate that the experimental procedure could measure the stratification profiles with a high degree of reproducibility and reliability.

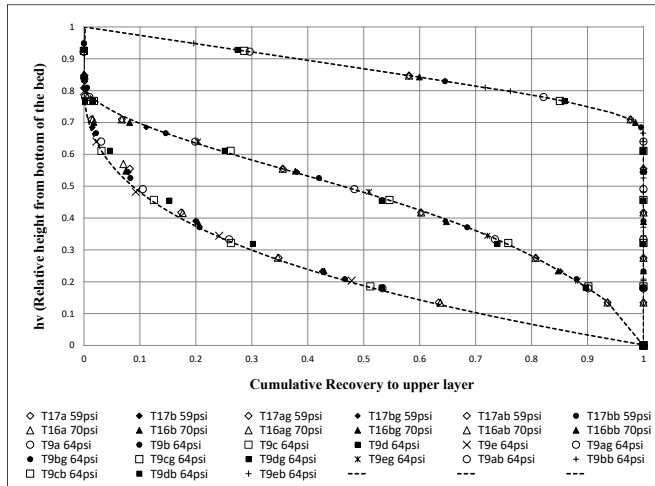


Figure 6: Equilibrium stratification profiles at different air-supply pressures

(Two replicates for tests T16 and T17 and 5 for test T9.)

(Profiles for red beads are designated a, b, c ...; for green ag, bg, cg ...; for boro ab, bb, cb ...)

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100mm, 22 – 26, 38%

The experimental design for the second investigation involved conducting series of tests, one for each of the relevant operating variables—%Stroke, bed depth, T1, and T2. Based on the experience gained in the first investigation, an estimate was made of the conditions that would yield the most sharply stratified profile. These conditions were selected as a ‘base case’ set of conditions for the testwork program. Each of the subsequent test series involved varying one of the relevant operating variables while holding all other operating conditions constant at their base case values.

Additional equilibrium profiles were extracted from the kinetic tests that were conducted later and are described in the follow-up study. Figure 7 gives an indication of the source of this additional data. It shows how the concentrations approach their value at equilibrium. The additional equilibrium stratification profiles were determined from data of this kind. (In passing, it can be noted from Figure 7 that the 999 second duration of equilibrium tests was easily long enough to ensure that equilibrium had been reached.)

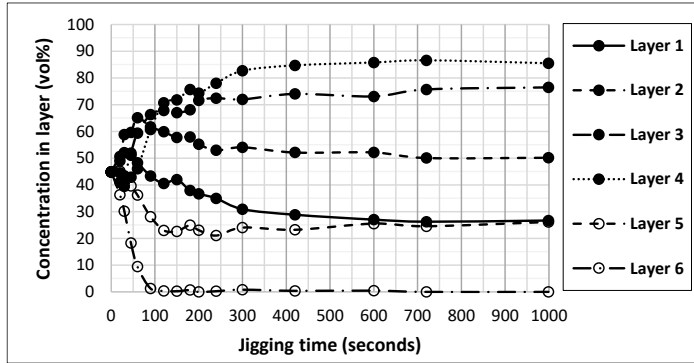


Figure 7: Example of stratification kinetics measured in the follow-up study

6. Results

6.1 The Influence of Bed Depth

Tests were conducted with bed depths of 70, 80, 90, 100, 120, and 150mm with the other operating variables held at their base case values. The equilibrium stratification profile was sharpest in the 90 and 100mm tests (Figure 8a). That set of profiles was taken as the standard against which all other profiles were compared and is shown as the heavy dashed lines in Figure 8 and subsequent figures. As will be seen, no other profiles found in the study were found to be sharper and so they will be referred to as the ‘optimum profiles’. All deviations from the optimum profiles were found to be in the direction indicated by the arrows in Figure 1a.

The profiles for the 80mm test (Figure 8b) were very close to optimum. The very slight deviation from the optimum profile for the heavy (red) component could perhaps be due to experimental error. The deviation is slightly greater for the 70mm test (Figure 8c) and becomes significant for the 120 mm test (Figure 8d). The deviation is even greater for the 150mm test, (Figure 8e) although part of the reason for this is that the feed composition in this test was inadvertently a little different from all other tests. (Figure 1b illustrates the kind of deviation that such an error can make.)

In summary, it appears that over a broad range of bed depths—from 80 to 100mm—the stratification profiles at equilibrium were essentially the same. Below and above this, stratification is increasingly less sharp. The deterioration is most marked for the heavy (red) component. These conclusions derive only from tests under the standard conditions indicated in Figure 8 and so remain tentative until the effect of other variables has been investigated.

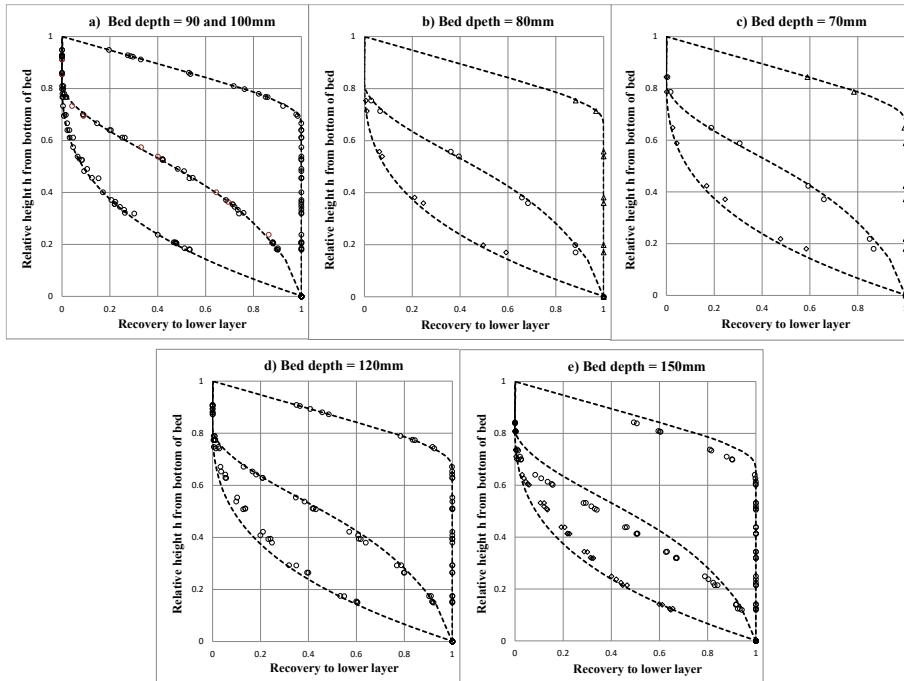


Figure 8: The effect of bed depth on the equilibrium stratification profile
 %Stroke = 38%; $T_1=0.22s$; $T_2=0.28s$; air pressure to piston=64psi

6.2 The Influence of Cycle Amplitude (%Stroke)

Tests were conducted with %Stroke values of 30, 34, 36, 38, 41, 45, 48, and 50% with the other operating variables at their base case values. The associated water displacements were estimated from the work described in Section 4 to be in the range from about 37 to 80mm.

In a similar way to the effect of bed depth, a broad range of values of %Stroke was found to give optimum stratification. As Figure 9a shows, the profiles aligned exactly with the optimum profiles for strokes from 34% to 41% (roughly equivalent to water displacements from 46 to 61mm). Below this range, i.e. at 30% stroke (Figure 9b), and above this range, from 45% to 50% (Figures 9c to 9e), the profiles increasingly diverged from optimum.

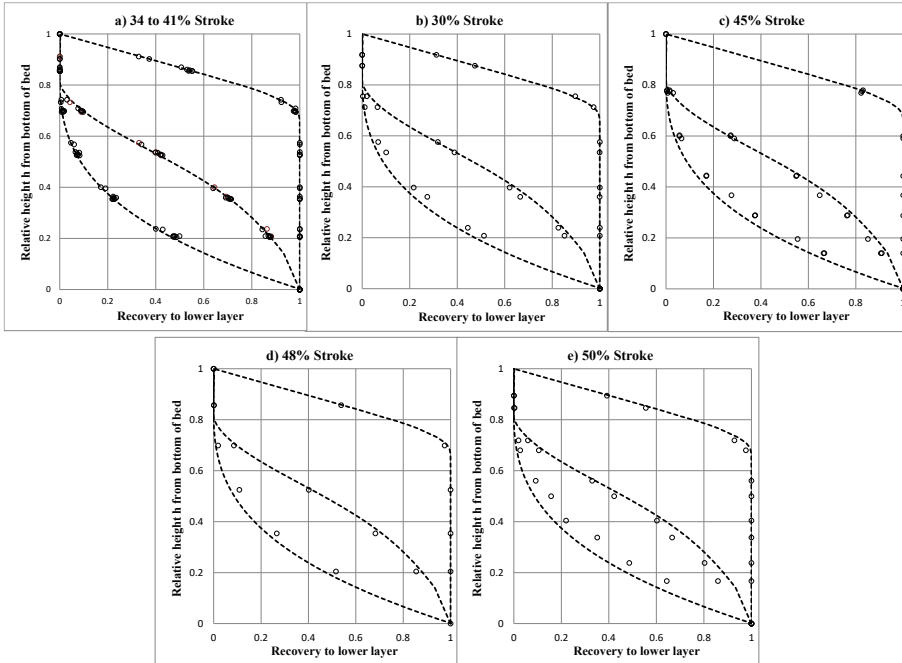


Figure 9: Effect of % Stroke on the equilibrium stratification profile
 Bed depth = 90mm; $T_1=0.22s$; $T_2=0.28s$; air pressure to piston=64psi

6.3 The Influence of the Pulsion Time, T_1 , and Pulsion Hold-time, T_2

The effect of the shape of the jig cycle on stratification was investigated for bed depths of both 90 and 100mm. Tests were conducted with pulsion times T_1 varying from 0.18 to 0.3 seconds (Figure 10) and with pulsion hold-times T_2 from 0.22 to 0.38 seconds (Figure 11). (Note that time periods in seconds correspond to the fraction of the duration of a 1 second cycle time; 0.2 seconds is equivalent to 0.2 of a 1 second cycle, for example.) All other operating variables were held at their base case values.

Figure 10 shows that varying the pulsion time T_1 had no effect on the stratification profiles. All profiles aligned exactly with the optimum when the bed depth was 90mm (Figure 10a) and almost exactly when the bed depth was 100mm (Figure 10b). The same good alignment was found with regard to the pulsion hold-time T_2 (Figure 11). The alignment was exact in tests with a bed depth of 90mm and with T_2 values of 0.24, 0.28 and 0.32 seconds (Figure 11a), and was almost exact when its value was 0.38 seconds (Figure 11b). There was a slight deviation in the alignment of heavy (red) profiles in tests with a 100mm bed depth (Figure 11c).

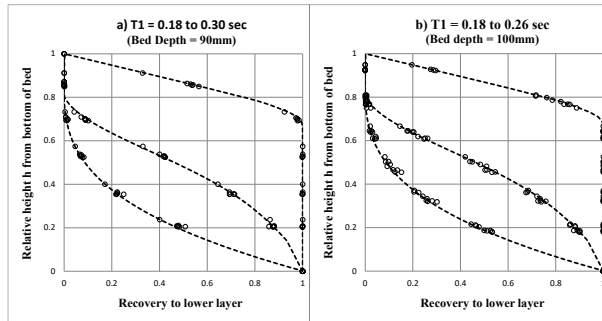


Figure 10: Effect of pulsion time, T1, on the equilibrium stratification profile
 %Stroke = 38%; T2=0.28s; air pressure to piston=64psi
 Bed depth = 90mm (a) and 100mm (b)

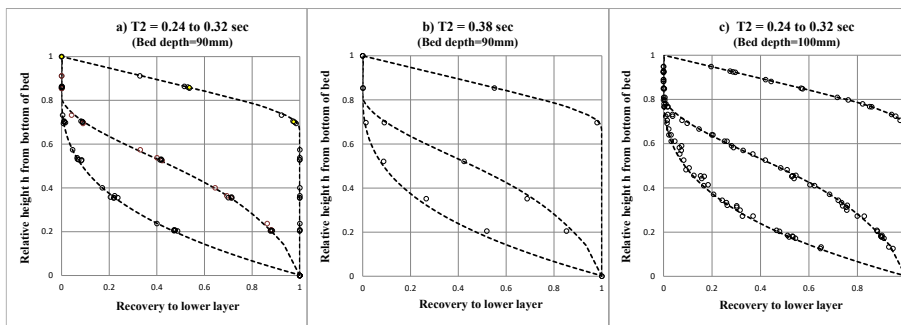


Figure 11: Effect of pulsion hold-time, T2, on the equilibrium stratification profile
 %Stroke = 38%; T1=0.22s; air pressure to piston=64psi
 Bed depth = 90mm (a) and (b) and 100mm (c)

6.4 Summary of Findings

The results of the study suggest that the stratification profile achieved in a jig at equilibrium is surprisingly independent of operating conditions. Provided the operating variables remained within an ‘optimum zone of operation’, the measured profiles were found to be essentially the same.

The optimum zone is defined in terms of the bed depth and %Stroke: respectively from 80 to 100mm bed depth and from 34 to 41%Stroke. Within this zone, the quality of stratification appears also to be essentially independent of the other three operating variables studied—the pulsion time T1, the pulsion hold-time T2, and the air-supply pressure (Figure 6). Outside the optimum zone the quality of stratification at equilibrium deteriorates; the jig bed at equilibrium becomes less sharply stratified as the stroke or bed depth move away from the optimum zone.

The range of values of %Stroke and bed depth which define the optimum zone are quite broad; the zone appears to be a relatively broad plateau rather than a localized high point. With respect to the %Stroke, the breadth of the zone (34 to 41%) corresponds to a range of water displacements from about 46mm to 60mm which is equivalent to a range from 5.7 to 7 particle diameters approximately. With respect to bed depth, the breadth of the zone (from 80 to 100mm) corresponds to a range from 10 to 12.5 particle diameters.

7. Limitations of the Study

The study findings have a number of limitations. Firstly, the experimental design employed had a limited ability to establish interaction effects and the full extent of the optimum zone of operations. However, given the extensive similarity of the equilibrium stratification profiles found, this limitation is probably not very significant.

The second limitation derives from the small size of the test jig—it was only 200 mm in diameter. This means that wall effects inevitably affected the nature of the stratification achieved. As noted by Woollacott (2019), the greater porosity of the bed adjacent to the jig chamber walls causes larger water flowrates in that region so that larger and denser particles tend to rise higher in the bed adjacent to the walls than they do in the main body of the bed. Although the full impact of this effect on stratification was not investigated, it was possible to estimate very roughly its extent based on the differences in colour of the bead components. It appeared that the wall effect did not extend more than about two particle diameters from the wall into the body of the bed. This corresponds to less than about 15% of the bed volume in the test jig being affected by the wall effect. However, whatever the exact nature of the wall effect, it did appear to be consistent so that the stratification profiles measured were very reproducible.

The suite of particles selected made the study somewhat academic in nature. The focus on density stratification made it necessary to use a system of essentially mono-size spherical beads. This limited the relevance of the study to the over-screen mode of jiggging in which no percolation of interstitial trickling occurs. In addition, a bed of mono-sized spherical particles has a higher bed porosity than is found in the more heterogeneous particle mixtures typical of jiggging practice (Woollacott, 2019; Kwan et al., 2013). The result of this is that the water displacements and bed depths associated with the optimum zone of operation were respectively slightly higher and lower than is typical of jiggging practice (Burt, 1984; Myburgh; 2010).

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8. Discussion

Despite its limitations, the study has yielded some significant and practical insights into the fundamentals of jiggging dynamics which, to the authors' knowledge, have not previously been reported. The most significant is the surprising finding that operating conditions had virtually no effect on the quality of stratification achieved at equilibrium provided those conditions remained within a broad range of values. This result is surprising because it is well known that operating conditions strongly influence jiggging performance. Before exploring the practical implications of this finding, it is appropriate to discuss its physical and theoretical plausibility.

The discussion begins with a focus on the obvious fact that inter-particle movement during jiggging is a key factor that determines the extent of stratification in a jig. If the water displacement is too small or too slow, the bed will not be dilated at all; no inter-particle movement will occur; and very little, if any, stratification will come about. If the water

displacement is too vigorous, the bed contents will to some degree be remixed in a way that disrupts the stratification that occurs. In between these two extremes there exists a region where the nature of the inter-particle movement is 'just right' for optimum stratification. At one boundary of this region, the water and bed displacements are not quite vigorous enough while at the opposite boundary they are just a little too vigorous. These observations align with the general findings of the study regarding an optimum zone of operation. Another conclusion from these observations is that the nature of the inter-particle movement occurring at these two boundaries is very different and that it must change quite considerably across the zone from one boundary to the other.

What is very surprising in the study findings is that the optimum zone was as broad and plateau-like as it was found to be. To put this in perspective, the extent of water displacement can change by 30% (from about 46 to 60mm) without having any noticeable effect on the stratification profile at equilibrium. The relative change in the bed displacement should be about the same over this range. With respect to the shape of the jig cycle, the value of T1 can change from 18 to 30% of a jig cycle—a 67% change—and the value of T2 can change from 24 to 38% of a jig cycle—a 58% change—without having any noticeable effect on the quality of stratification at equilibrium. Further, a change in the depth of the bed from 80 to 100mm—a 25% change—had little effect on the stratification profile at equilibrium.

All these quite extensive variations in operating conditions cause or influence the very extensive change in the nature of inter-particle movement that exists across the optimum zone. It is very surprising then that the same equilibrium stratification profile is achieved despite the extensive variation in conditions that occur within the bed across the optimum zone.

These effects can be explained from jiggling theory. The fundamental phenomenological insight behind King's model is that the nature of the stratification profile in a jig is determined by the balance between stratification and diffusive forces (King, 2001); at equilibrium, the fluxes from these two forces balance. Accordingly, it is not so much the extent of the inter-particle movement that affects the quality of stratification, but the balance of stratification and diffusive forces that occur as a result of that inter-particle movement. On this basis, the plateau-like nature of the optimum zone suggests that, at equilibrium, the balance of stratification and diffusive forces is the same across the optimum zone despite the fact that the nature of the inter-particle movement changes considerably. This observation suggests that the inter-particle movement in the bed at equilibrium influences both stratification and diffusion dynamics in exactly the same way, at least when that inter-particle movement is neither too vigorous nor too constrained. Such a conclusion seems reasonable given that inter-particle movement is responsible for both the stratification and diffusion of particles in the bed.

9. Practical Implications

There are numerous practical implications of the findings of this study. The most obvious is that jiggling is shown to be a very robust technology for separating particles on the basis of differences in their density. It appears that within an optimum zone of operations all operating conditions can vary across a fairly wide range of values without affecting the quality of stratification achieved at equilibrium.

The most significant implication of the study, however, is that the influence of operating conditions on jiggling performance must derive from their influence on stratification kinetics

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The similar argument applies with regard to the effect of bed depth, because the amount of material in the bed should also affect the extent of inter-particle movement in the bed. In this case, however, the effect acts in reverse. For a given pattern of water displacement, the inter-particle movement is likely to be greatest when there is only a little material in the bed. It would be expected that the extent of that movement would decrease with an increase in the amount of material in the bed because of the dampening effect which particles have on each other's movement in a fluid.

The similar argument applies with regard to the effect of bed depth, because the amount of material in the bed should also affect the extent of inter-particle movement in the bed. In this case, however, the effect acts in reverse. For a given pattern of water displacement, the inter-particle movement is likely to be greatest when there is only a little material in the bed. It would be expected that the extent of that movement would decrease with an increase in the amount of material in the bed because of the dampening effect which particles have on each other's movement in a fluid. Therefore, it would be expected that there would be a 'goldilocks zone' where the mutual dampening of particle movement in the bed would be just right for optimal stratification. Too little material would result in insufficient dampening and excessive movement and therefore poorer stratification. Too much material would dampen movement too much also leading to poorer stratification.

rather than from their influence on stratification at equilibrium. This makes sense because although stratification and diffusional dynamics balance at equilibrium, they do not do so while the particle bed is moving from a homogenous condition at the start of jiggling to its condition at equilibrium. It is therefore most likely that the variations in the conditions within the bed that occur across the optimum zone will have an effect on stratification kinetics in a way that they do not at equilibrium.

The implication of this observation is that it is important to disentangle kinetic and equilibrium effects when thinking about the optimization of jig performance or when troubleshooting performance that is below par. In this regard, the equilibrium stratification profile should be thought of as indicating the quality of stratification that *can* be achieved *inherently*. Further, it is determined by the *properties* of the particles being treated, not by the operating conditions, provided these remain within a broad range of optimum values. Put another way, the findings of this study imply that the purpose of adjusting the operating conditions in a jig is to improve stratification kinetics, not to improve what is inherently possible for the jig to achieve at equilibrium. Operating conditions should be adjusted to improve the rate at which stratification progresses, and to allow sufficient time for it to progress to an equilibrium condition.

This point can be illustrated further by considering material that is 'difficult to stratify' because the densities of some particles are not very different. Figures 8 to 11 shows that a jig is capable of achieving very distinct stratification even when the density difference between particles is as small as 91 kg/m^3 (a specific gravity difference of 0.091). However, a small difference in density may very well lead to slow stratification kinetics, and consequently to insufficient time being allowed for stratification to progress to what is achievable at equilibrium. In this context, a manipulation of jiggling conditions will not change what inherently can be achieved by the jig, but it could accelerate the progress of stratification and also ensure that sufficient time is made available to get close to equilibrium and the stratification profile that it is inherently possible to achieve in that jig.

10. Conclusions

Despite its limitations and academic nature, the study has yielded some useful results. After establishing that only four independent operating variables were likely to influence stratification in the test jig, the study showed that a zone of optimum jiggling conditions existed in which none of these variables had any noticeable effect on stratification at equilibrium. Although the nature of the inter-particle movement varied significantly across this region, it did not appear to affect the balance between stratification and diffusional dynamics that determine the nature of stratification at equilibrium. The most significant implication of these findings is that the influence which operating variables have on jig performance seem to derive from their influence on stratification kinetics and not from their influence on stratification at equilibrium.

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